



Testing of Densified Liquid Hydrogen Stratification in a Scale Model Propellant Tank

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SUMMARY

This paper describes a test program that was conducted at NASA to demonstrate the ability to load densified LH₂ into a subscale propellant tank. This work was done through a collaborative effort between NASA Glenn Research Center and the Lockheed Martin Michoud Space Systems (LMMSS). The Multilobe tank, which was made from composite materials similar to that to be used on X-33, was formed from two lobes with a center septum. Test results are shown for data that was collected on filling the subscale tank with densified liquid hydrogen (DLH₂) propellant that was produced at the NASA Plum Brook Station. Data is compared to analytical predictions. Data collected for this test series agrees well with analytical predictions of the environmental heat leak into the tank and the thermal stratification characteristics of the hydrogen propellant in the tank as it was filled with DLH₂.

INTRODUCTION

NASA has identified propellant densification as a critical technology in the development of the single stage to orbit (SSTO) reusable launch vehicle (RLV) designated by Lockheed Martin as the VentureStar™. The densification of cryogenic propellant through subcooling allows 8 to 10 percent more propellant to be stored in a given volume. This allows for higher propellant mass fractions than would otherwise be possible with conventional, normal boiling point cryogenic fluids.

To date, several aspects of densification technology have been investigated. Previous tests at NASA have been conducted with a subscale liquid hydrogen densifier (ref. 1). This test hardware was built and tested to prove the ability to produce DLH₂ at 2 lbm/sec. The next step after production of densified LH₂ was to investigate the particulars of performing the sequential process necessary to load a propellant tank with densified propellants. This report details the tests that were conducted at NASA Plum Brook Station in Sandusky, Ohio to demonstrate the ability to load DLH₂ into a subscale propellant tank.

Lockheed Martin Michoud Space Systems (LMMSS) personnel have developed an analytical tool that models the loading of a tank of specific geometry with densified liquid hydrogen. For a propellant tank filled with normal boiling point (NBP) liquid hydrogen, and a specified external heat flux, the tool models the total time required to replace the NBP liquid hydrogen with densified liquid hydrogen and the final fluid conditions.

The test program described here was conducted to demonstrate the ability to load a scale model propellant tank with densified liquid hydrogen and to validate the LMMSS analytical model. The plan was to produce, in a batch process, densified liquid hydrogen and then transfer it to a scale model propellant liquid hydrogen tank. This test program was conducted jointly through a Space Act Agreement between NASA Glenn Research Center in Cleveland, Ohio, and Lockheed Martin Michoud Space Systems in New Orleans, Louisiana.

TEST OBJECTIVES

The purpose of the tests reported here was to perform the sequential propellant tank loading and simulate the recirculation process using DLH₂ propellant with a tank configuration that is traceable to RLV. The tests were designed to characterize and demonstrate tank thermal stratification, a necessary requirement for the definition of optimum loading, densifier design and production operations in the RLV environment. Another important objective was to evaluate the thermal conditions at which LH₂ could be maintained in its subcooled state during a simulated recirculation of DLH₂. Furthermore, a subscale tank loading demonstration program could provide the data and information necessary to firmly ground the analytical tank models developed by LMMSS. The specific test objectives were as follows:

1. Characterize the LMMSS Multilobe tank environmental heat leak.
2. Produce batch quantities of 27 R LH₂ working fluid in a facility dewar to simulate tank recirculation of densified propellant.
3. Demonstrate the ability of LH₂ to flow upwards out of the tank via a vertical siphon.
4. Evaluate "load-and-go" tank filling with DLH₂ on an ambient temperature and prechilled Multilobe tank.
5. Demonstrate and verify tank thermal stratification characteristics over a range of inlet LH₂ recirculation flow rates.
6. Obtain sufficient LH₂ thermodynamic data of tanking operations to allow validation of mathematical-analytical tank models developed.

FACILITY AND TEST HARDWARE

Test Facility

The K-Site test facility at NASA Glenn Research Center Plum Brook Station is used for large-scale tests that utilize liquid hydrogen. Utilities were provided for filling, pressurizing, draining, and inerting the Multilobe Tank.

The Multilobe Tank was situated within a structural steel frame, which had a roof to protect the tank, as well as scaffolding to provide access to the tank and piping. The tank sat on a platform ~4 ft above grade.

Liquid hydrogen was provided at the site with two liquid hydrogen trailers. The capacity of each trailer was 13 250 gal. Working pressure for each trailer was 100 psig. One trailer (designated H24) was used to produce densified liquid hydrogen by pulling vacuum on the ullage using vacuum pump VP-5. VP-5 was a mechanical vacuum pump with a capacity of 850 ft³/min. H24 was modified to allow the ullage to see negative pressure. The second trailer (designated H25) was used as a catch tank during the recirculation simulation.

Liquid hydrogen was transferred from the trailers to the test tank through 2 in. vacuum-jacketed piping. Piping was also provided for venting the tank ullage, and pressurizing the tank with either gaseous hydrogen or gaseous helium. A schematic of the test facility is shown in figure 1.

Instrumentation was provided to monitor test and facility parameters. Temperatures, pressures, liquid hydrogen flow rates, and tank strains were all monitored. Data was recorded using a facility data acquisition system. Data was updated once per second, and could be recorded at the rate of 1 scan/sec, 1 scan/10 sec, or 1 scan/min. The total number of channels monitored was 364.

Test Article

The Multilobe Liquid Hydrogen tank is fabricated from composite material, and consists of two lobes. Each lobe measures 5 ft in diameter, is 17 ft long, is joined at a 10° angle, and contains a barrel section, a web and two domes. The lobe to lobe joint contains a continuous 1/4 in. K-type Raco seal. The joint is assembled with 176 (5/8-in.-diameter) bolts. The assembled tank is covered with foam insulation to prevent ice formation and to maintain liquid hydrogen temperatures.

Tank empty weight is 1500 lb. Total tank volume including ullage is ~483 ft³. Surface area of the tank is estimated to be ~400 ft².

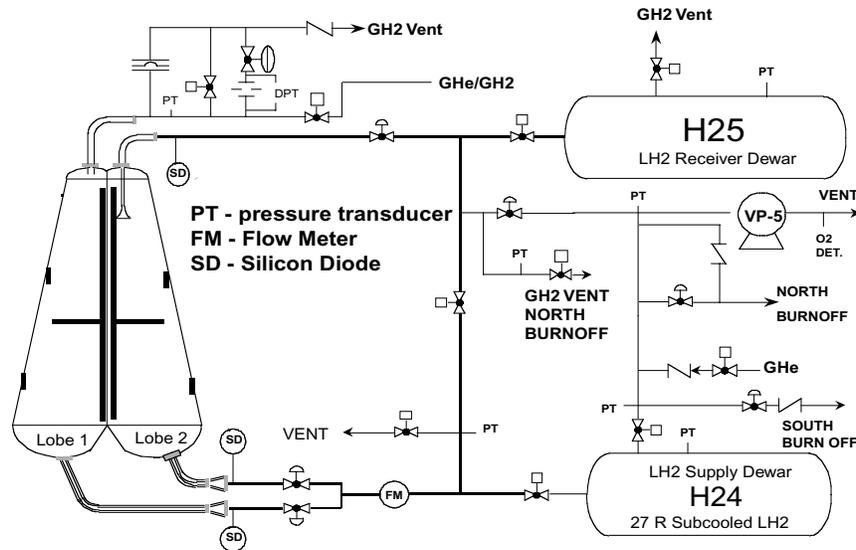


Figure 1.—Multilobe Tank Thermal Stratification Simplified Schematic.

There are two inlet ports, one in the bottom of each lobe of the tank. These inlet lines are 1-1/2 in. pipe size flanged connections. There are two outlet ports, one in the top of each lobe of the tank. The outlet port in lobe one is a vapor vent line. The outlet port in lobe two is a siphon line to drain liquid from the top of the tank. The end of the siphon line is located ~24 in. below the top of the tank.

INSTRUMENTATION

The Multilobe Tank was instrumented with a number of silicon diode temperature sensors. These sensors were located inside the tank. Several silicon diodes were mounted on the wall of the tank, several were mounted on the web connecting the two halves of the tank. The balance of the silicon diodes were mounted on rakes inside the tank, and were used to monitor the temperature profile of liquid inside the tank. There were two rakes, one mounted in each lobe. A schematic indicating the location of these silicon diodes is shown in figure 2. A total of 54 silicon diodes were monitored during testing to determine the LH₂ temperature profile in the tank.

TEST MATRIX

For the tests reported here, densified LH₂ was generated inside supply dewar H24 by gradually reducing pressure over the fluid with the vacuum pumping system. The dewar pump-down time from 15 to 1.5 psia took between 12 and 16 hr. Once DLH₂ at the target temperature of 27 R was produced, it was pressure transferred from dewar H24 into the bottom of the Multilobe tank while normal boiling point fluid was siphoned off the top. This flow scheme (filling DLH₂ from the bottom while siphoning warmer LH₂ from the top) provides the best method for filling the tank with densified propellant (ref. 3). The liquid siphoned off the top of the tank flowed to the second dewar H25. Table I is a summary of the tests.

ANALYTICAL MODEL

The mathematical simulation of the densification process developed by LMMSS is based upon a multiple-node, Lagrangian approach in which the liquid is subdivided into a number of moving small bundles of fluid. The model is called the Multilobe, MultiLayer Densification Model (ML2DM). The diagram in figure 3 shows the general schematic of the model for a number of different multiple lobe tank configurations.

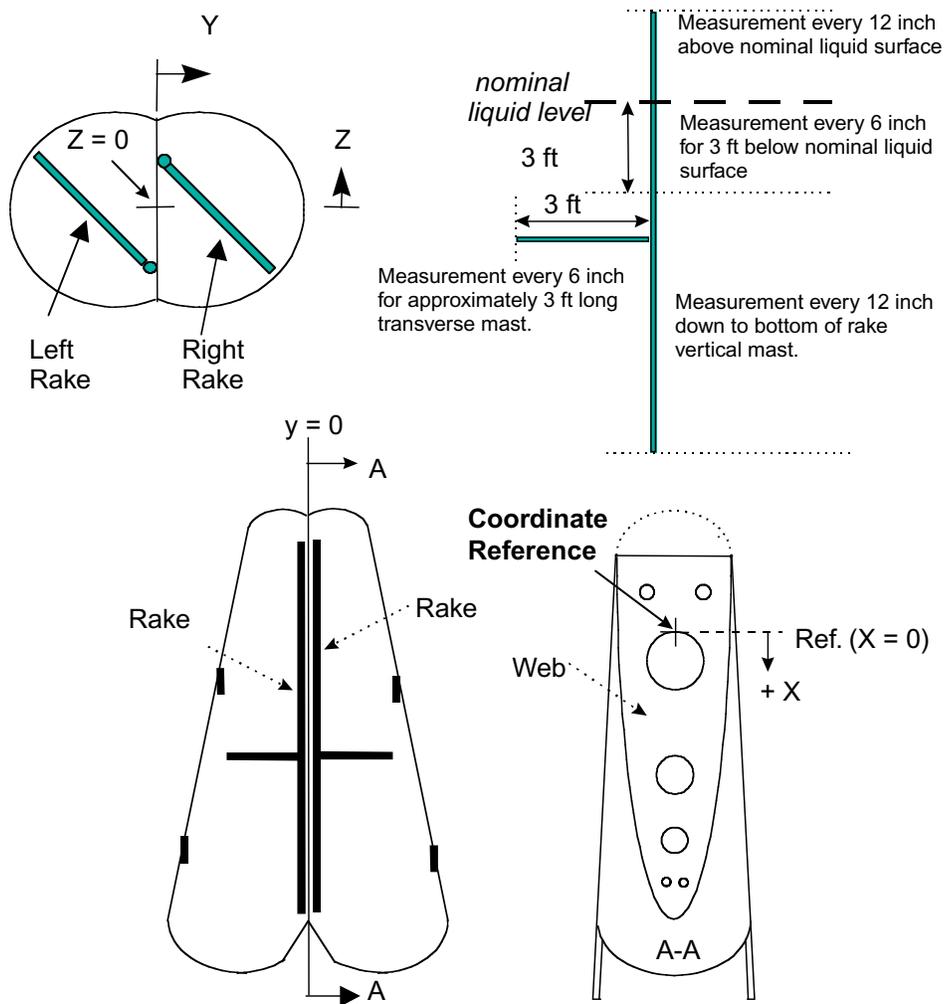


Figure 2.—Silicon diode rake subassembly installation for test tank.

TABLE I.—TEST MATRIX

Test number	Test description	Initial tank conditions	Number of fill lines used	LH ₂ transfer flow rate, lbm/sec	Run time, min	Tank pressure, psia
1	Boil off	Filled w/NBP LH ₂	n/a	0.0	125	15
2	Saturated siphon	Filled w/sat'd LH ₂ at 30 psia	2	0.6 – 1.5	25	30
3	Straight load-and-go	Empty, Ambient	2	1.5	155	18 – 20
4	Pre-chilled load-and-go	Empty, Cold	1	1.5	250	18 – 20
5	Recirculation simulation	Filled w/NBP LH ₂	1	0.5	120	30
6	Recirculation simulation	Filled w/NBP LH ₂	1	1.0	60	30
7	Recirculation simulation	Filled w/NBP LH ₂	1	1.5	40	30
8	Recirculation simulation	Filled w/NBP LH ₂	2	0.5	90	30
9	Recirculation simulation	Filled w/NBP LH ₂	1	0.5	125	30

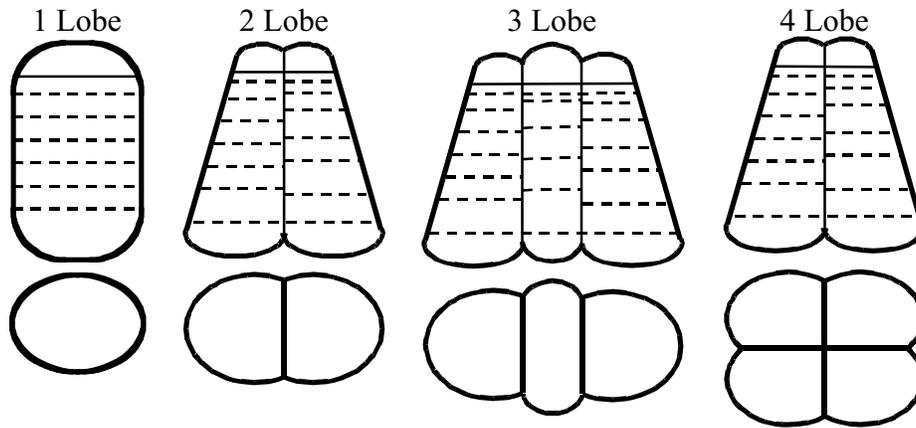


Figure 3.—General schematic of ML2DM.

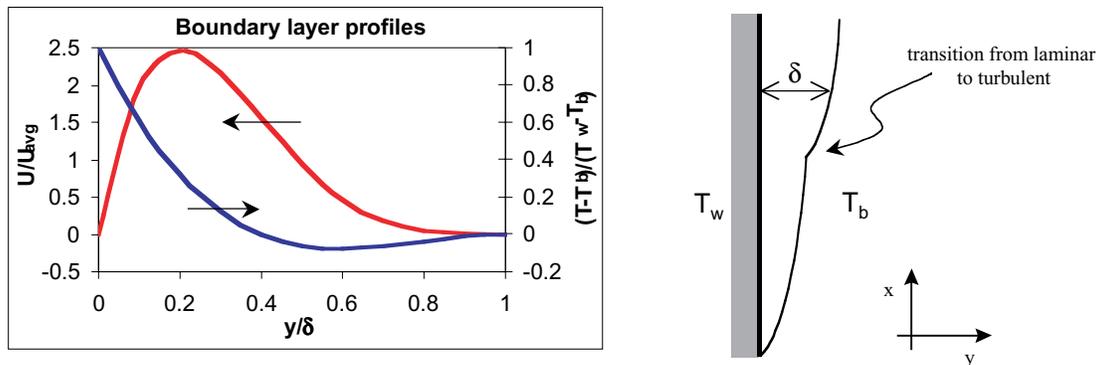


Figure 4.—Buoyancy driven boundary layer temperature and velocity profiles.

The fluid is subdivided into the separate lobes of the tank and then further subdivided into layers. During the recirculation cycle, subcooled fluid is flowed into the bottom of the tank and warmer fluid is siphoned from the upper portion of the tank. Within the simulation, as the fluid enters, nodes are created at the bottom of the tank. The conditions of each node are then tracked as it is pushed upward by the recirculation process. At the top of the tank where fluid is being removed, the nodes shrink and eventually collapse.

In addition to the slow bulk movement of the liquid caused by the recirculation flow there are a handful of other significant effects that control the effectiveness and efficiency of the densification process. One of these is the formation of buoyancy driven boundary layer flows and another is the lobe-to-lobe interaction of the fluid. Both of these phenomena are discussed in somewhat more detail.

Buoyancy driven boundary layer flow is significant in the densification process because it causes a redistribution of the energy within the tank. The continuous heat leak into a nonvacuum jacketed propellant tank can be quite significant. This influx of energy tends to work against the densification process which is, at its core, essentially a bulk enthalpy lowering exercise. However, due to the existence of buoyancy driven boundary layer flow, the detrimental effects of the continuous heat leak is significantly minimized since it tends to draw the fluid warmed along the walls upward towards the top of the fluid where it can be siphoned off. Thus, this boundary layer flow amplifies the thermal stratification within the tank and thereby enhances the densification process.

In figure 4 the assumed velocity and temperature profiles are shown along with a simple schematic of the fluid near the tank sidewall. There are no exact analytical solutions to the governing differential equations for motion and temperature distribution of the fluid within such a thermal convection boundary layer of fluid along the sidewall of the tank. The fluid boundary layer profiles used in this analysis come from a unique approximate solution in which the temperature profile follows a third order polynomial and the velocity profile follows a fifth order polynomial. All of the boundary conditions imposed at the wall and at the boundary layer to bulk fluid interface are satisfied by

this system of equations though conservation of energy is not satisfied along the full breadth of the profile. This fact is compensated by the assumption that the boundary layer thickness is proportional to the Grashoff number to the 1/4th power in the laminar region and to the 1/3rd power in the turbulent region. The empirical nature of these last correlations, largely verified by this testing, far outweighs the slight errors inherent within the approximate solution to the boundary layer equations. The result is a straightforward algorithm, which correlates well with the test results presented in the next section.

The second significant feature of the analytical model and the second significant phenomenon occurring within the tank during the densification process is the lobe-to-lobe interaction of the fluid. This is especially significant to the densification process when the inflow, outflow, and/or tank configuration has a large asymmetry as was the case for these tests where inflow and outflow was located in different lobes. The Multilobe tank described within this paper is a two-lobe configuration with a single separating septum. This septum is not solid, but it does offer some restriction in the lobe-to-lobe cross flow. The simulation handles the calculation of this cross flow by first reducing the number of lobe-to-lobe, node-to-node interactions into eleven possibilities. These interaction possibilities for each combination of adjoining, moving nodes is evaluated at a given time step and is then superimposed against the fixed geometry of the septum. The relative fluid flow resistance and fluid acceleration damping used within the simulation was based on standard orifice flow calculations. The model to test data comparisons presented in the next section confirmed the validity of using such values.

Other features of the model include a single node, multiple gas ullage simulation, bulk boiling and surface condensation algorithms, as well as an approximate algorithm to simulate convection motion of the bulk fluid.

TEST RESULTS

The results from the testing can be broken into three categories. First there was the saturated siphon test which was an operations demonstration. Second, there were two “load and go” tests, which were attempts to demonstrate potential alternative tank loading methods with densified propellant. Third, there were five recirculation tests that were intended both to fully demonstrate the baseline densification process and to provide data for the validation of the analytical model.

The saturated siphon test was intended to demonstrate the fact that saturated cryogenic fluid could be flowed upwards and out of the tank via a vertical siphon. The fluid in the tank was fully saturated at ~30 psia and then flow was initiated. Because the fluid was static and saturated within the tank initially, the rise to a higher elevation and the acquisition of velocity should have cavitated the fluid slightly. The question going into the test was whether this low level cavitation would be detrimental to the siphoning process.

Figure 5 shows two plots. The first is the inflow of liquid hydrogen to the tank while liquid hydrogen flowed out the siphon. Because the liquid level within the tank was held constant and because there was little or no thermal stratification within the tank, the outflow up the siphon is equated to this inflow value. Reasonably steady flow was obtained at both a lower value (~0.7 lbm/sec) and at a higher value (~1.6 lbm/sec). The second plot in figure 4 shows the measured temperatures both in the vicinity of the siphon inlet within the tank and in the siphon line itself. This confirms, based upon the tank pressure, that the fluid was fully saturated.

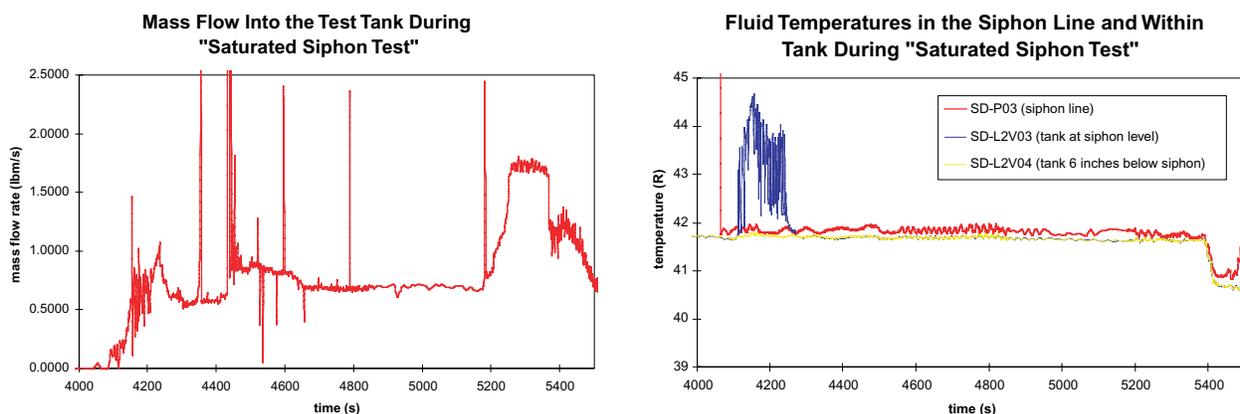


Figure 5.—Saturated siphon test results.

The second category of tests undertaken were two “load and go” tests. The purpose of these tests was to load densified propellants directly into an empty tank with no recirculation. If this could be done on a launch vehicle such that an acceptable degree of overall bulk subcooling was achieved, then there would be no need to have a recirculation system in place. The first “load and go” test, called the “straight load and go,” began with a warm empty tank. For the second “load and go” test, called the “prechilled load and go,” the tank was first prechilled by filling with normal boiling point fluid, then drained, and then refilled with the densified propellant.

The results from the straight load and go test are presented in figure 6 and the results from the prechilled load and go test are presented in figure 7. Each of these plots shows the temperature time histories of the various silicon diode temperature measurements mounted on the vertical rake within the tank. As the tank was filled from the bottom, the diodes fell into place at cryogenic temperatures. The diodes at the bottom of the tank near the in-flowing subcooled liquid became and remained the coldest. However, as the fluid rose it picked up heat so that by the time that the uppermost diode saw liquid it saw nearly saturated fluid. The prechilling of the tank appeared to alleviate this effect somewhat as the temperatures were generally lower through the tank than during the “straight load and go” test. However, neither loading scenario achieved a complete top-to-bottom subcooling of the liquid. Also, in both of these cases, as soon as the liquid inflow was stopped the overall bulk temperature rose quickly. If this tank had been within a flight vehicle on the launch pad experiencing a prelaunch hold it is likely that the undensifying, expanding liquid would have been expelled out the vent.

The final category of tests undertaken within this test plan were five recirculation and densification tests run at various inflow rates and configurations. These tests were intended both to fully demonstrate propellant densification as it would be applied to a launch vehicle and to validate the mathematical simulation of the in-tank densification process. There were five tests, listed as Test 5 to 9 in table I. Plots for Test 5 to 9 are shown in figures 8 to 12, showing comparisons between simulation reconstructions of the test conditions and the actual test data itself after completion of loading with DLH₂. The test data points presented are the silicon diode temperature measurements up the vertical rakes, one in each lobe, and the lines of simulation output are the predicted thermal stratification

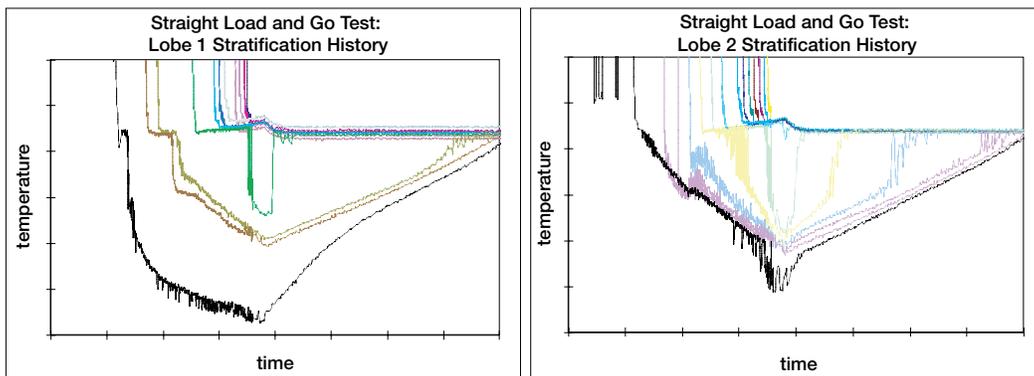


Figure 6.—Straight load and go test results.

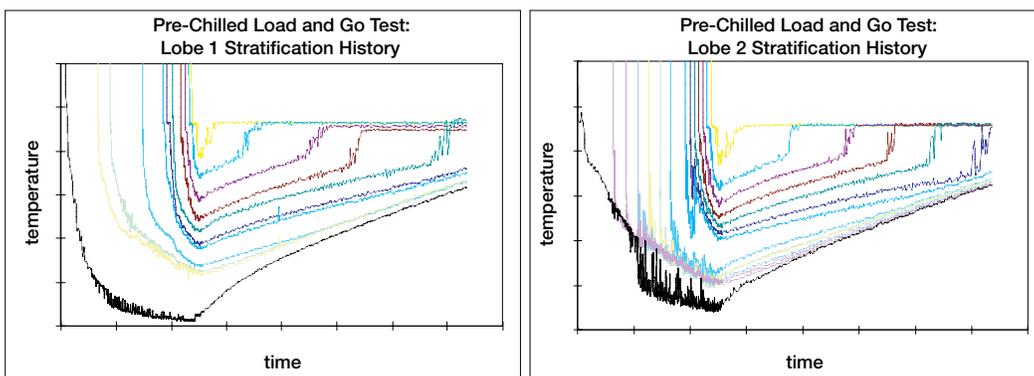


Figure 7.—Prechilled load and go test results.

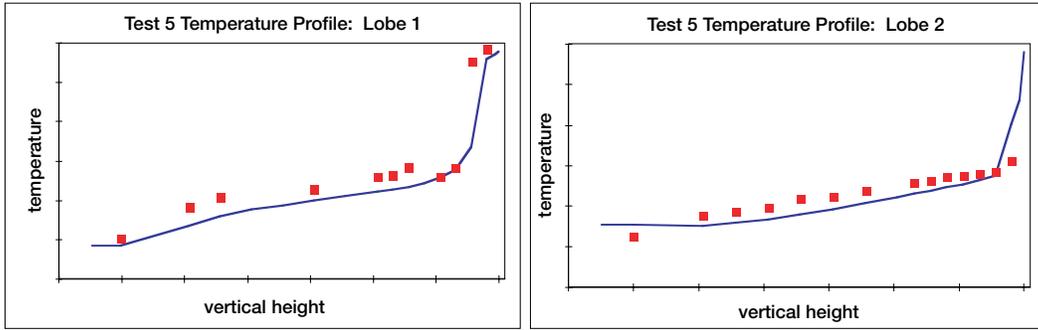


Figure 8.—Test 5 thermal stratification profiles at end of DLH₂ fill.

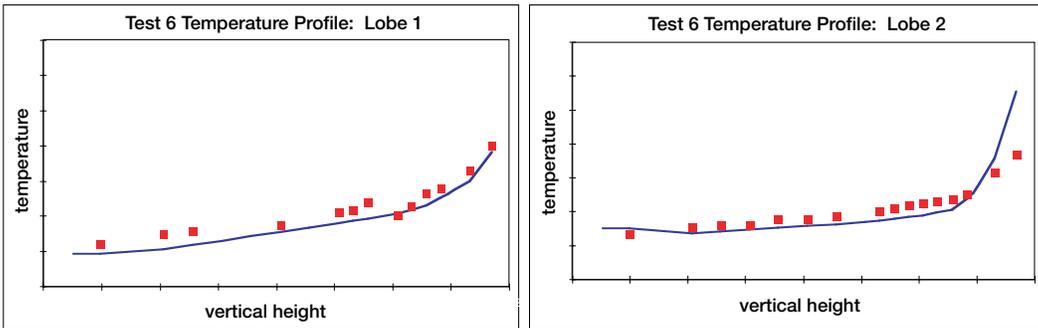


Figure 9.—Test 6 thermal stratification profiles at end of DLH₂ fill.

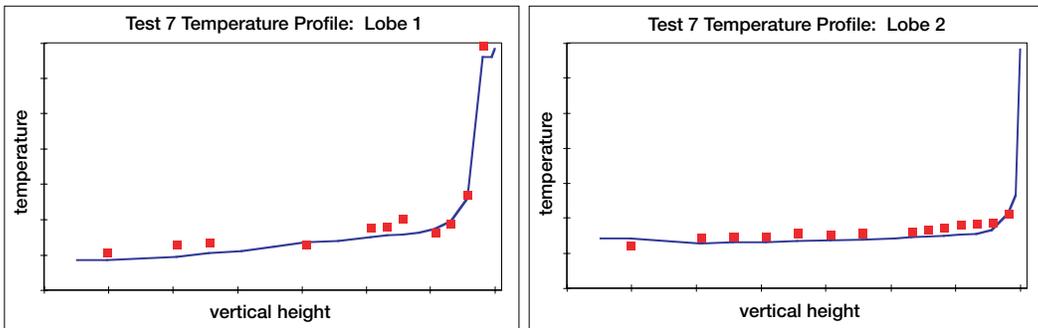


Figure 10.—Test 7 thermal stratification profiles at end of DLH₂ fill.

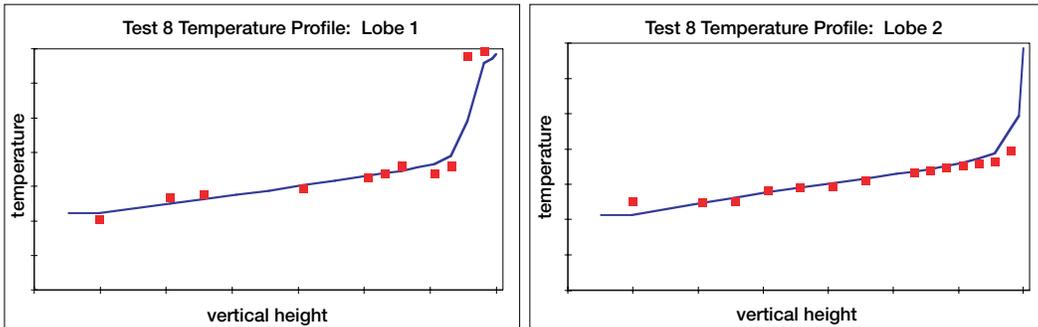


Figure 11.—Test 8 thermal stratification profiles at end of DLH₂ fill.

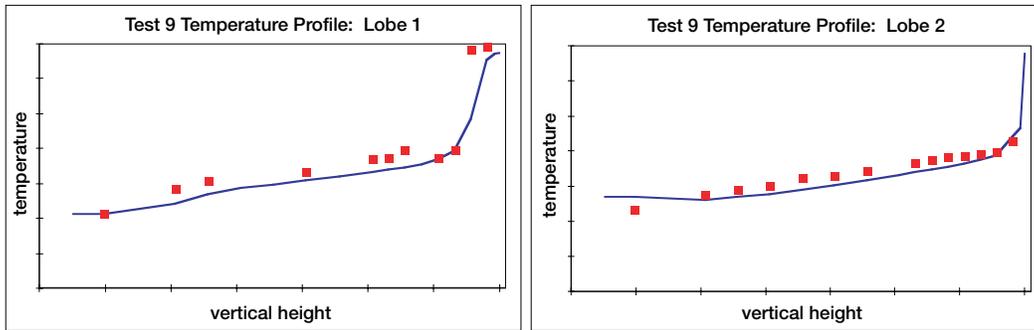


Figure 12.—Test 9 thermal stratification profiles at end of DLH₂ fill.

TABLE II.—APPROXIMATE ERROR IN LOADED MASS

Test	Description	Approximate error in loaded mass, percent
5	≈0.5 lbm/s 1 inlet	0.53
6	≈1 lbm/s 1 inlet	0.33
7	≈1.5 lbm/s 1 inlet	0.16
8	≈0.5 lbm/s 2 inlets	0.06
9	≈0.5 lbm/s 1 inlet	0.36

profiles. Such data to simulation comparisons were made at many points along the densification timeline but due to space restrictions only the steady state plots are presented.

For nearly all the tests, the agreement between the measured test data and the simulation was quite good. Table II summarizes the accuracy of the simulation based upon estimated total mass loaded within the tank. Total mass was estimated from final fluid density and the tank geometry. With the exception of one test, Test 5 the first recirculation test conducted, all of the error values are within the accuracy range resulting from the accuracy of the diodes. The attempt to come to a better understanding of the relatively large error on Test 5 is ongoing.

CONCLUSIONS

Data collected from this test program leads to the following observations and conclusions:

1. Environmental heat leak into the Multilobe tank was consistent with predictions.
2. Saturated liquid hydrogen can be flowed upwards and out of the tank via a vertical siphon, proving that siphoning saturated liquid hydrogen from the top of the tank will not adversely affect recirculation.
3. Neither “load and go” loading scenario (either with a warm tank or a prechilled tank) achieved a satisfactory top-to-bottom subcooling of the liquid.
4. For recirculation simulation tests, agreement between measured test data and analytical predictions was good, which validates the model.
5. Tank thermal stratification characteristics over a range of inlet LH₂ recirculation flow rates was demonstrated and verified.

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